Faraday Rechargeable Battery System

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Acknowledgement

We would like to express our special thanks of gratitude to our advisor, Dr. Taufik, who gave us the opportunity to do this wonderful project on our topic, Faraday's Law of Induction, which has helped us to put a lot of time into researching this topic and we came to know about so many new things that we are extremely thankful for. Another special thanks to the company, Linear Technology, who provided us with a demo board that was instrumental in completing our project. Lastly, we would like to thank our family and friends who helped provide us with support and encouragement during each step of this project.

Abstract:

The modern electronic age has given birth to a variety of innovative and hand-held devices that are carried with the consumer nearly 24 hours a day, seven days a week. The one shortfall of these devices is their energy storage, or in most cases, a battery. The Faraday Rechargeable Battery System is a unique system that will generate electricity through rotational movement of a tire. This can be a bike, a car, or any other transportation vehicle that uses wheels for movement. The kinetic energy that is engendered either by the user or an engine can then be converted into usable electricity. This electricity can then be used for a variety of things which includes powering a front and back LED for bike riding at night, can recharge the removable battery, and capable of interfacing with small electronic devices, such as cell phones, mp3 players and tablets, via standard USB connections. Until now, no company has offered a solution for charging a battery, powering a lighting system, and the ability to charge external devices via the USB connection.

Chapter 1: Introduction

Electricity generation is one of the most important factors in supporting 21st century society and economy. The world consumes over 23,000 TWhr of electricity every year and that number is only increasing [1]. Much of this electricity is still generated with dangerous and outdated technologies centered on the burning of fossil fuels. The continued burning of fossil fuels will have catastrophic impacts on humanity. This danger can be mitigated through clean and innovative techniques of energy harvesting. One process has been utilized in more ways than one is Faraday's law of induction shown in Figure 1-1. As the magnet is rotated, a time-varying magnetic field is applied to the coil inducing a voltage across the coil. This technique can also be reversed with the coil varying and the magnet being stationary.

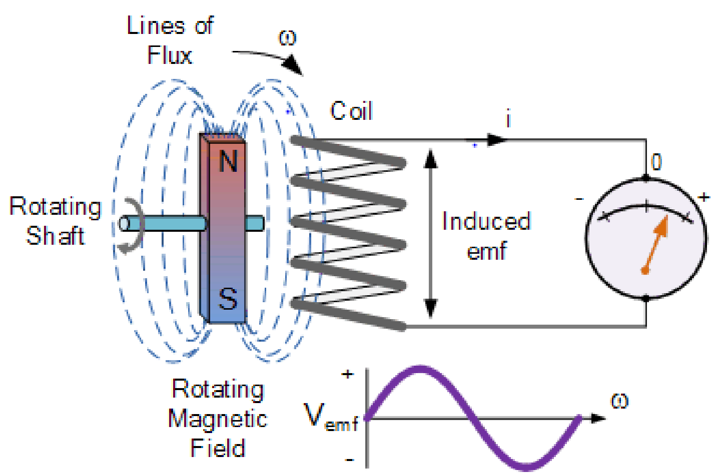

Figure 1-1: Faraday's Law of Electromagnetic Induction

If our energy consumption continues this reliance on fossil fuels, at this rate without us looking for more aggressive and consumer friendly alternate forms of energy, such as our device, our planet will face serious environmental impacts. You can see from Figure 1-2 that most of the energy consumed in 2013 is produced with the use of fossil fuels, while a very small portion is created from renewable or nuclear options. The current reliance on fossil fuels, as shown in Figure 1-2, indicates a daunting task. The technology that we are trying to develop, and many other forms of energy-harvesting technologies, are trying to increase the share of renewables to reduce greenhouse gases produced by energy production. This technology could also be implemented in rural areas around the world. It is estimated that 1.2 billion people today do not have access to electricity [2]. A simple technology like this could allow for some devices to be powered on command without the need for an expensive electrical grid or power plant.

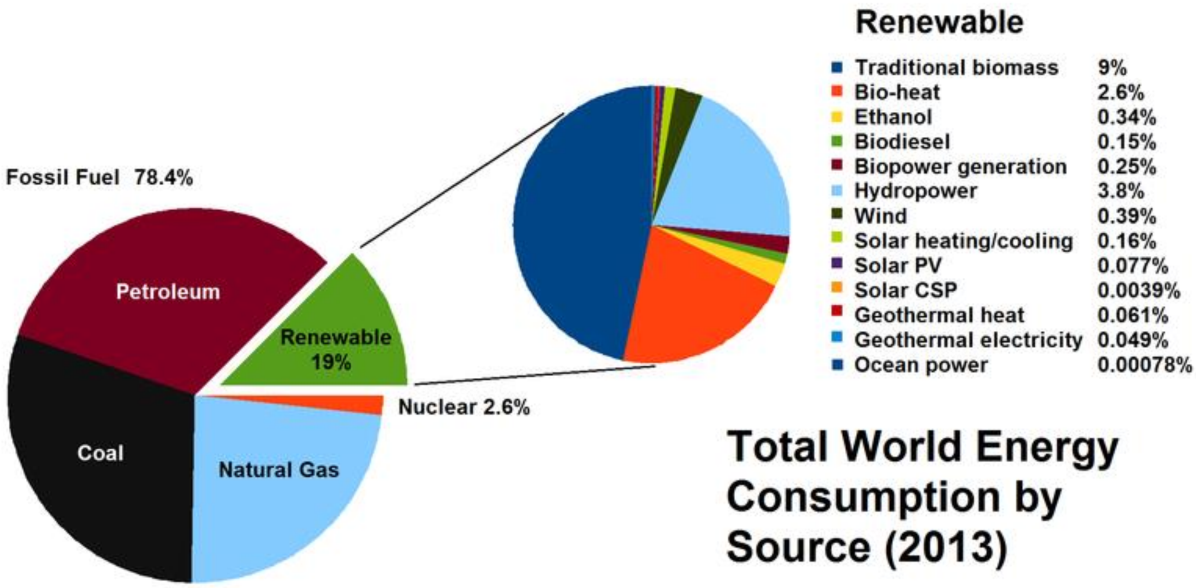

Figure 1-2: Total World Energy Consumption (2013)

Chapter 2: Background

Energy production around the world has been steadily increasing over the last thirty years. In 1985, the world was using just under 10,000 terawatt hours. In the year 2014, the world produced over 23,000 TWhr of electricity. The graph in Figure 2-1 shows the trends for electricity consumption around the world. The interesting thing about this graph is the relatively constant production of electricity in North America and Europe. However, the large increase in electricity production in the Asia Pacific is indicative of the developing juggernaut of China.

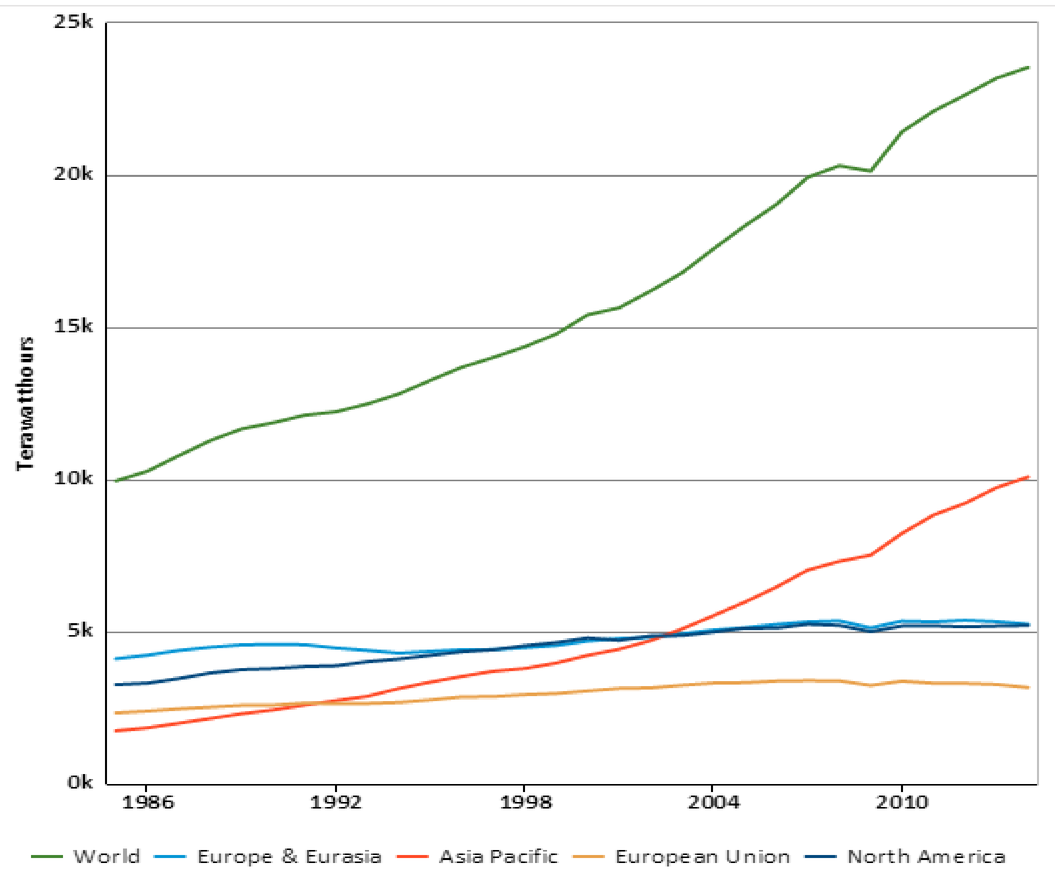

Figure 2-1: Electricity Consumption Over the Last 30 Years

The troubling truth about this is that China's energy production comes from nonrenewable sources including a vast usage of coal. The entire world's use of coal can be seen in Figure 2-2. As shown, China is using 2.8 Million tons of oil equivalent (Mtoe) while the entire world is using 3.8 Mtoe with many countries reducing their reliance on it.

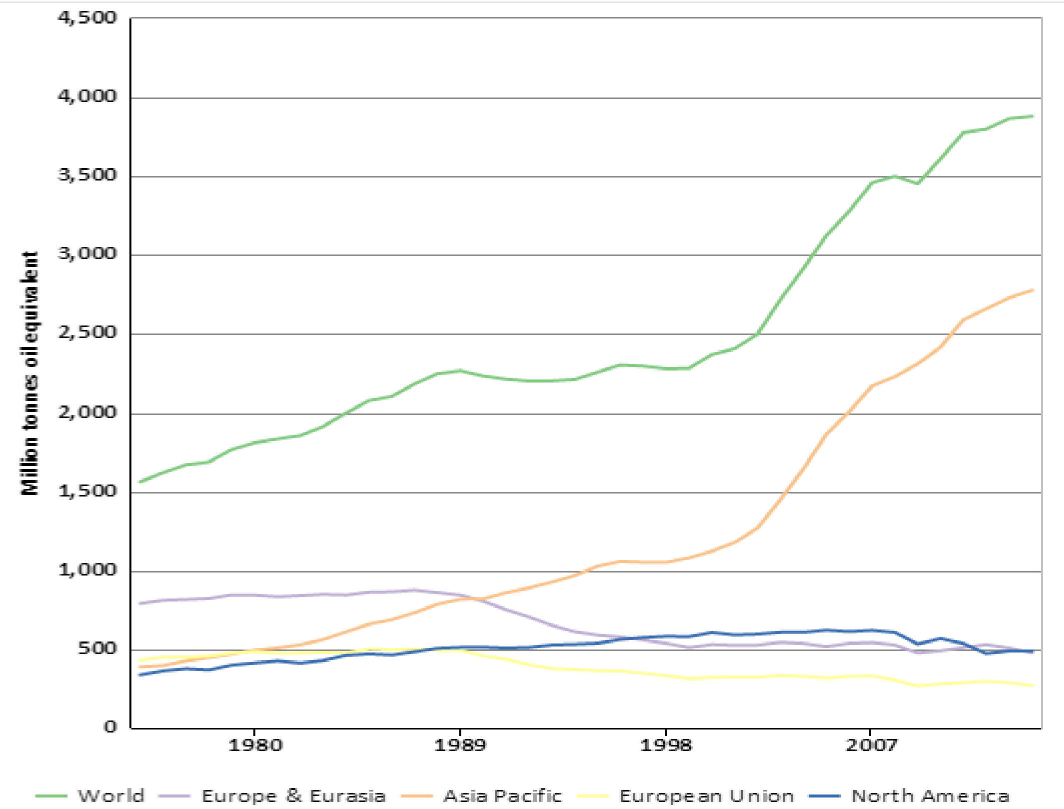

Figure 2-2: World Consumption of Coal in Mtoe

The method by which electricity is generated depends on the fuel being used. For most fossil fuel electricity generation including those with natural gas, coal, and oil the method is through burning the material, and turning a steam turbine generator. But other forms of electricity generation also exist that do not involve burning fossil fuels. Some of these alternatives include solar, wind, hydroelectric, nuclear and geothermal/biofuel. Solar electricity generation utilizes the sun’s light waves to generate an electric current. Wind and hydroelectric both use turbines to generate electricity through the wind or flowing water respectively. Nuclear power is similar to how fossil fuels generate electricity. Water is turned into steam to power a turbine but the heating process for nuclear is free from CO_2 release. The same can be said for geothermal and biofuel generation technique that also utilize the steam turbine for electricity generation. These are the main forms of large scale energy production around the world with all types of forms being integrated into the grid.

Smaller scale electricity generation has also become a large industry. One of these methods is using a crankshaft to turn a magnetic through a coil of wire to induce a voltage. This same technique is used in many applications including a shake flashlight that utilizes a magnetic and a coil to generate a voltage. As the magnetic moves back and forth through the coil, an alternating current can be generated. Small-scale solar has also been increasingly used on the roofs of houses and business, but also in the realm of electricity generation for personal devices.

Cal Poly has a history of energy harvesting projects. The first project is the Energy Harvesting from Exercise Machines which seeks to harness the energy generated by people using exercise machines and delivers that energy back to the electric grid. There contains three main components being worked on are the protection system, DC-DC converter, and an inverter. The DC-DC converter takes in the power from the exercise machines and then converts that to a manageable voltage level for the inverter. One problem that this project still faces is that the inverter may overload the converter, this overload is caused by the inverter demanding more current at a lower voltage than what the DC-DC converter can provide. The second project is the DC House Project which aims to provide electricity to geographically hard-to-reach areas. The DC House project offers rural electrification to individuals as opposed to the whole community. This makes the DC House scalable, affordable, and flexible. That's accomplished by operating its components and system based on low-power, low-voltage DC electrical system to directly run DC loads, bypassing losses associated with traditional AC voltage system.

The goal of this project is to design an environmentally friendly and user friendly portable rechargeable battery capable of interfacing with small electronic devices, such as cell phones, mp3 players and tablets, via standard USB connections. The design of this project will be to build the most user friendly and intuitive product to minimize possible user errors and make using our product as simple as tying your shoe. The Faraday Rechargeable Battery, as stated in the name of the product, utilizes Faraday’s Law of

Induction which states that by passing a magnet through a coil of wire, a small electrical current is created and then stored then used to power the USB device. The purpose here is to provide an innovative, user friendly, environmentally safe way to provide battery power for various devices.

Chapter 3: Design Requirements

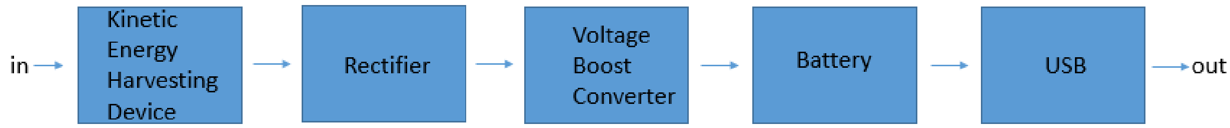

Figure 3-1: High-Level System Block Diagram

The block diagram shown in Figure 3-1 describes the input and output of the proposed Faraday Rechargeable Battery System. The input to the kinetic energy harvesting device will be created by the bike user physically pedaling. This will result in a fluctuating sinusoidal wave. We then need to pass that wave through a rectifier to make the signal a constant DC voltage. A constant DC voltage is needed to charge our battery and output from the USB. Since we want our output to work with a USB connection we need the output voltage to be 5V. This will require us to boost the output of our rectifier which can be achieved using a boost converter. That boosted voltage will then be stored in a battery for future use via the USB output connection.

The completed system will have two available inputs. The main input is the alternating current signal produced from the kinetic energy harvesting block. The kinetic energy will be generated by the user through pedaling a bicycle or accelerating in a car. This will provide the power from the rest of the circuit to operate. A secondary input can be found on the removable battery. This battery can be recharged through a MicroUSB port when the battery is not present in the bicycle system. There are three outputs of the system. The first output is from the battery to the USB port where electronic devices can be charged. Another output powers the on-board lighting system. Since the lights will primarily be used at night time, there will be a switch controlling whether the lights are on or not. This gives the user flexibility when using the system. The last output is to the battery itself. If the user is not using the lighting system and not charging an external USB powered device, the system will only charge the battery for use at a later time. This gives the system an extraordinary amount of flexibility as the battery can be used to power the lights when riding alone isn't enough. Table 3-1 shows each design requirement as well as the engineering specification that our design will follow. The requirements for this device were developed with careful consideration of our competitor's products and how we could make our design robust as possible. Table 3-2 indicates the functional inputs and outputs of the system.

Table 3-1: Requirements and Associated Engineering Specifications

Requirement	Engineering Specifications	Justification
Compact for ease of use	Small and portable ● Box containing circuitry (7.5 inch. tall, 3 inch. wide, 1.2 inch. deep) ● Average initial setup time should not exceed 30 minutes	Based on competitor device packaging size and estimated installation times
Able to withstand outdoor weather conditions	Weatherproof casing and hermetic sealing	Product needs to be protected from weather and other possible external damage
Universally configurable for different bike frames	Attachment system based on either clips or magnet	Must be able to be moved from one bike to another,
Output provides 500mA of current	Regulated 5V USB output and capable of charging a 3.7V Lithium Ion Battery	Able to charge using USB connection

Table 3-2: Faraday Rechargeable Battery System Top Level Functionality

Input/Output	Type	Description
Input	Power	Kinetic Energy from the rotation of the wheel will generate an alternating current.
Input	MicroUSB Power	Power input to the battery from an external source.
Output	USB	Connection from battery to external USB-powered device.
Output	LED	Connection to front and rear LEDs
Output	Battery	Connection for charging battery through kinetic energy conversion.

Chapter 4: Design and Component Selections

The first step of this design was to figure out the correct chips to harvest energy at low voltages. After researching the different techniques for energy harvesting, piezoelectric energy harvesting was the method chosen. This method allows for mechanical kinetic energy to be converted into electrical energy through electromagnetic induction. We found that the only chips that we were able to use were from the IC distributor Linear Technology. Specifically, LTC3588-1/2, were the chips chosen because they contain an internal full wave bridge rectifier. We decided that we wanted the chips to have an internal rectifier as opposed to making one ourselves to allow us to keep the size of our overall package down. The first chip, LTC3588-2, would have the best chip for us to use due to its selectable output voltage of 5V which is needed for the USB output. However, it required an input voltage in the 14-20V range. The second chip, LTC3588-1, could also be used due to its selectable output voltage of 2.5V which we would have needed to double. This chip's input voltage range was a bit larger from 2.7-20V which gave us more flexibility if our piezoelectric device outputted a low voltage.

An important factor in the design phase was to make the system compact. The system diagram shown in Figure 4-1 indicates the different subsystems used. The human user is the input to the piezoelectric device, once the mechanical energy has been converted to electrical energy, the device is inputted to the LTC3588-1 demo board. The utilization of this device reduced the component from two independent integrated circuits into one package. The output of the board is varying output at 1.8, 2.5, 3.3 or 3.6V.

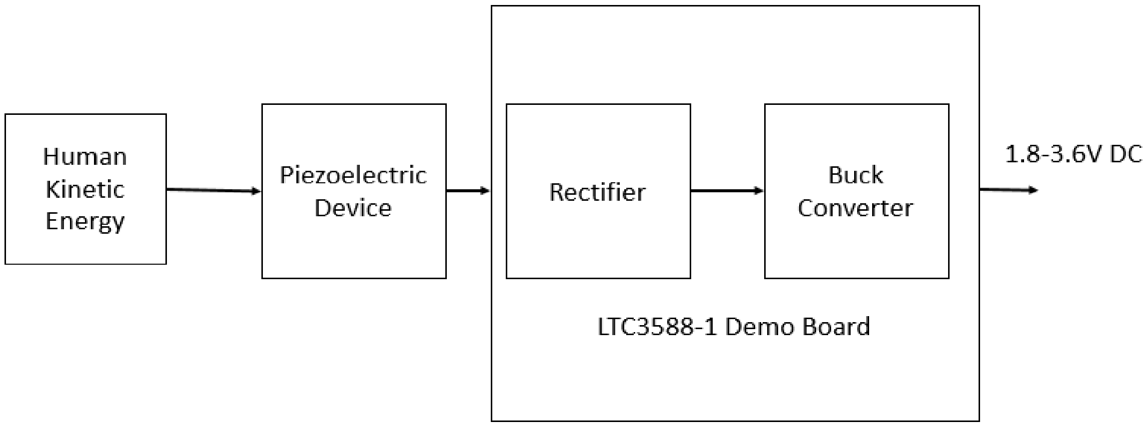

Figure 4-1: Complete System Diagram

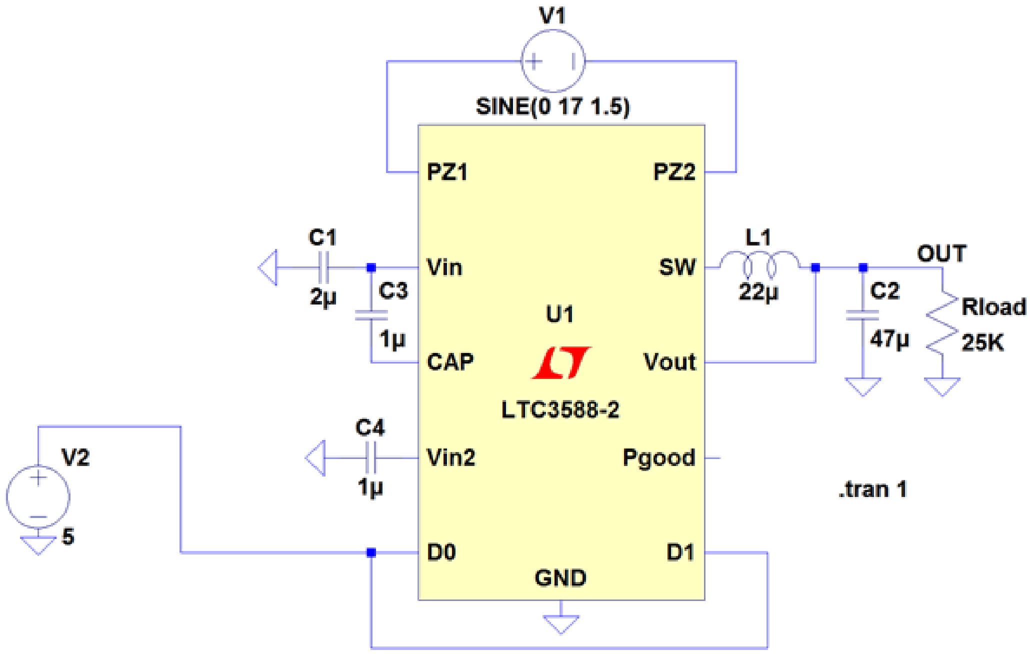

Figure 4-2: LTspice Schematic w/ 5V Output (LTC3588-2)

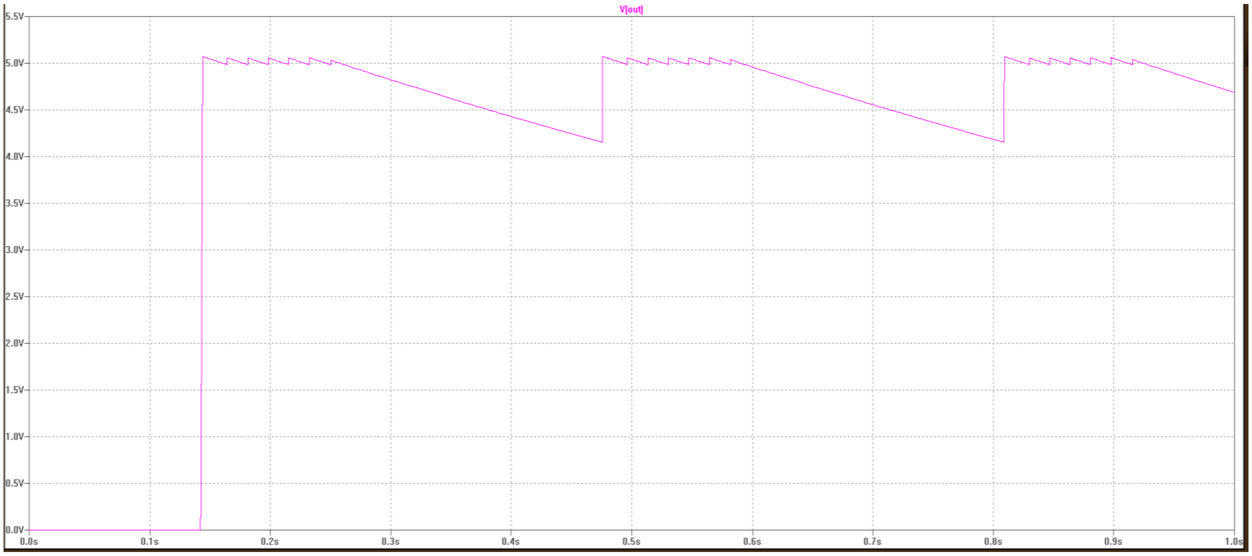

Figure 4-3: Simulated 5V Output (LTC3588-2)

Our next step was to simulate these two chips using LTspice to see the theoretical minimum input voltage required for turn on. Since we used an LT chip we were able to use the Test Fixture feature on LTspice to test our chip. As shown in Figure 4-2 you can see the minimum required input voltage for the LTC3588-2 is 17V and Figure 4-3 shows the desired 5V output. Figure 4-4 shows the minimum required input voltage for the LTC3588-1 is 9V and Figure 4-5 shows the desired 2.5V output.

We decided to order both chips just in case our input voltage from our piezoelectric device wasn't as high as we expected. When the chips were ordered, the packages of the integrated circuits were MSOP-10. The ICs were very hard to deal with due to the small package size, flat pins and a ground plane on the bottom of the chip that was inaccessible to the dual inline package adapter. This was remedied by ordering the demo board version of the LTC3588-1.

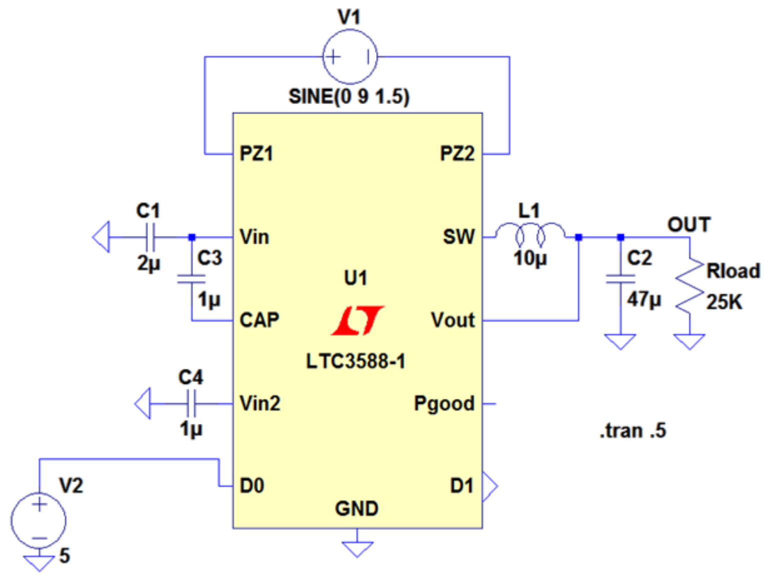

Figure 4-4: LTspice Schematic w/ 2.5V Output (LTC3588-1)

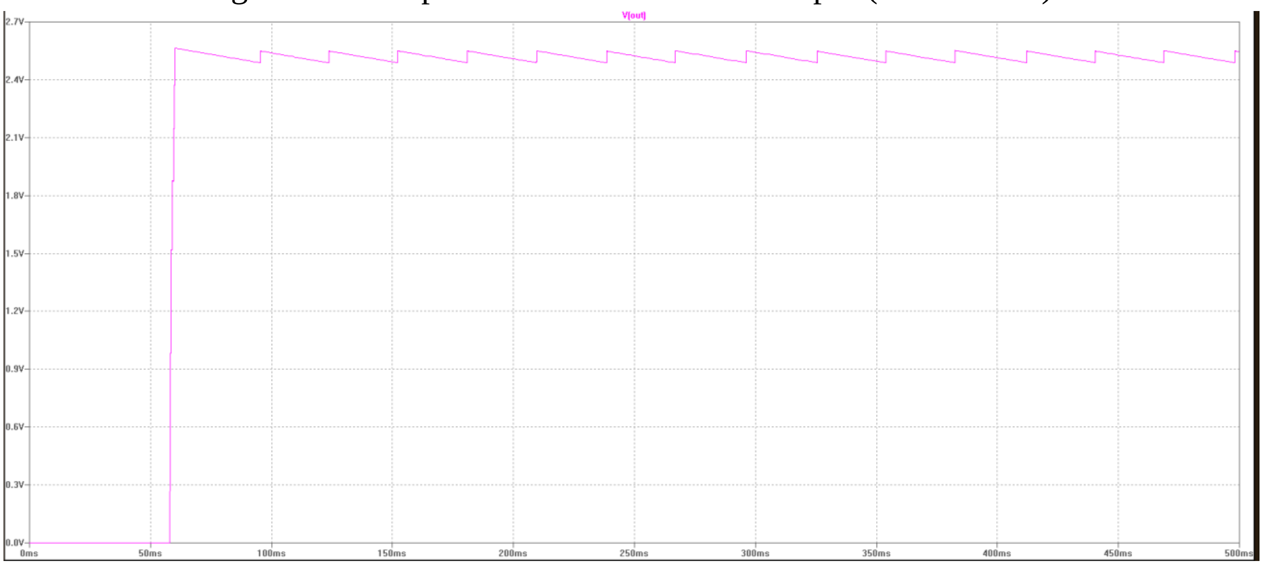

Figure 4-5: Simulated 2.5V Output (LTC3588-1)

Once the energy harvesting circuitry was designed and simulated, the next step was to design the piezoelectric device that will convert mechanical energy into electrical energy. The preliminary design used Faraday's law of induction. This law states that if a time-varying magnetic field is applied to a coil of wire, an electromotive force (EMF) will be produced across the coil. The faster the magnetic field changes through the coil, the higher the EMF that will produced. The EMF can also be increased by increasing the number of coils that the magnet passes through. This limited the design variables to two.

Since the time-varying magnetic field will change at a very high number of rates, changing the number of coils was the only real choice for the design. The next step in the piezoelectric device was the choice of magnet. Since the intensity of the magnetic field was a determiner for the output EMF, neodymium magnet was chosen. The dimensions of the magnet was also given by the casing for the coil and magnet. The inner diameter of the housing for the magnet was 1”. This gave an upper limit for the diameter of the magnet. With this in mind, a neodymium magnet with 36 lbs of pull force and having a diameter of ¾” and 1” long. This allowed the magnet to fit inside the housing as well as slide back and forth with relative ease. The final device is shown in Figure 4-6.

Figure 4-6: Piezoelectric Device

Figure 4-7 shows the individual components of our piezoelectric device. Our piezoelectric device consists of the following parts: plastic cap with rubber stopper, tube with coil, and neodymium magnet. The plastic cap was used to contain the neodymium magnet inside the plastic tube during testing. As we worked on our project we realized the magnet would occasionally get stuck in the cap. To prevent this we decided to glue rubber stoppers inside the cap to not only prevent the magnet getting stuck but to also increase the speed that magnet moved through the coil. The coil was then made by putting two pieces of tape one inch apart in the center of the tube and then looping over 2000 coils to produce the desired voltage.

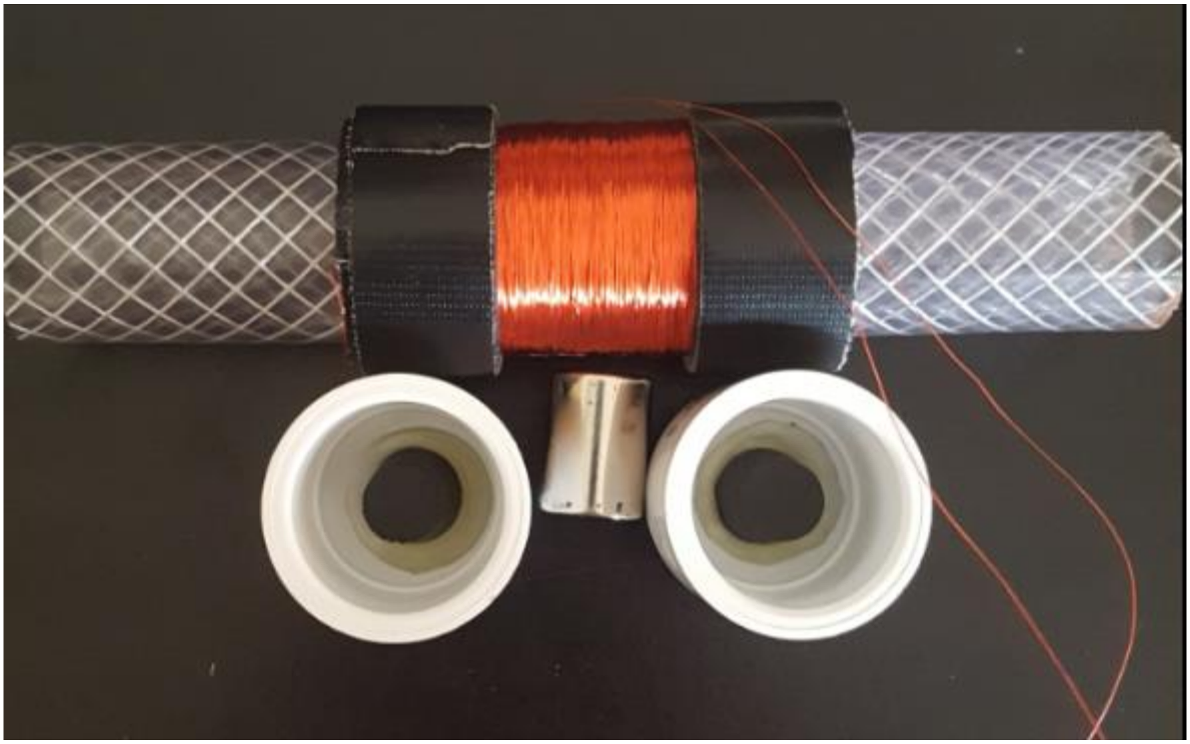

Figure 4-7: Individual Components of Piezoelectric Device

Chapter 5: Hardware Test and Results

Once the design was completed and implemented, the testing process began. We first started testing our piezoelectric device with no load. Figures 5-1 and 5-2 show our two different no load tests. Figure 5-1 was captured when our device was shaken with a constant frequency to get an indication of the output voltage. This output ranged from 18-21 Vpp. Figure 5-2 was captured when our device was shaken much more vigorously to simulate the rotation of a wheel. The output with the increased shake speed resulted in an increased voltage range of 30-36Vpp.

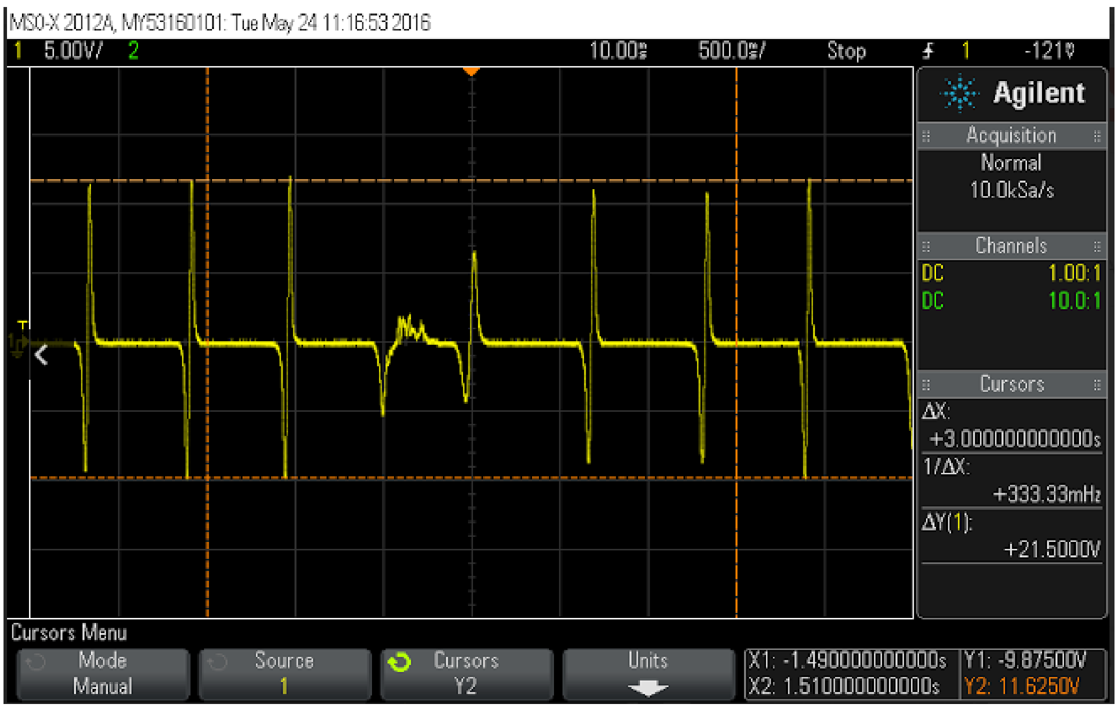

Figure 5-1: Piezoelectric No Load Test

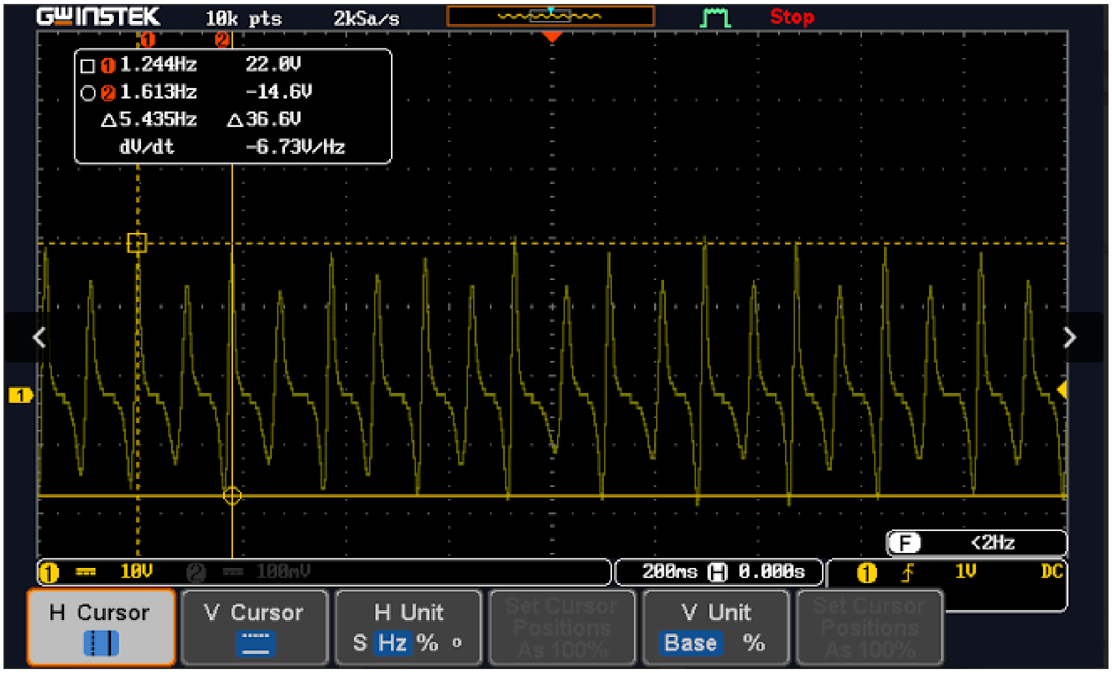

Figure 5-2: Piezoelectric No Load Fast Test

We then moved on to begin testing the LTC3588-1 demo board with a function generator and no load. Figure 5-3 shows the 2.5V output option from the demo board. The input sine wave was tuned to 1.5Hz because in previous test trials, the human shaking of the piezoelectric device was at a rate of about 1-2 cycles per second.

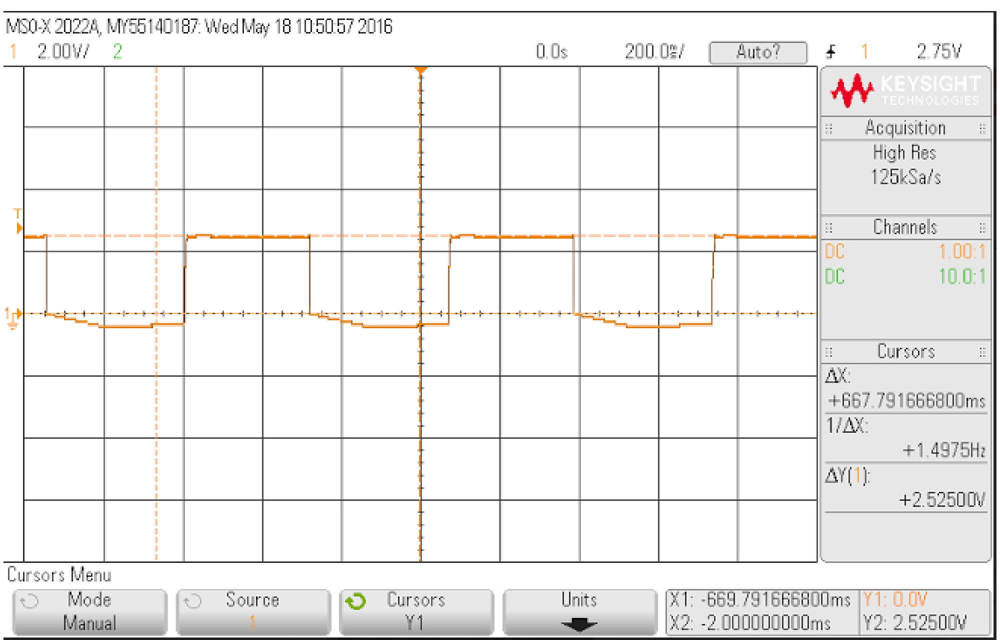

Figure 5-3: Chip Output 2.5V

Once the demo board was properly initiated and tested to confirm it was functioning properly, a resistive load was applied to the output. Figure 5-4 below shows the output with a 100Ω resistive load. This capture shows the complete cycle of the magnet passing in and out of the coil in the piezoelectric device. As the magnet passes through, the voltage is spiked above the threshold of the LTC3588-1 where it is rectified and then regulated to output around 2.5V. Figure 5-5 shows the similar discharge but with a load of 1kΩ. The discharge is caused by the large capacitance at the output of the demo board.

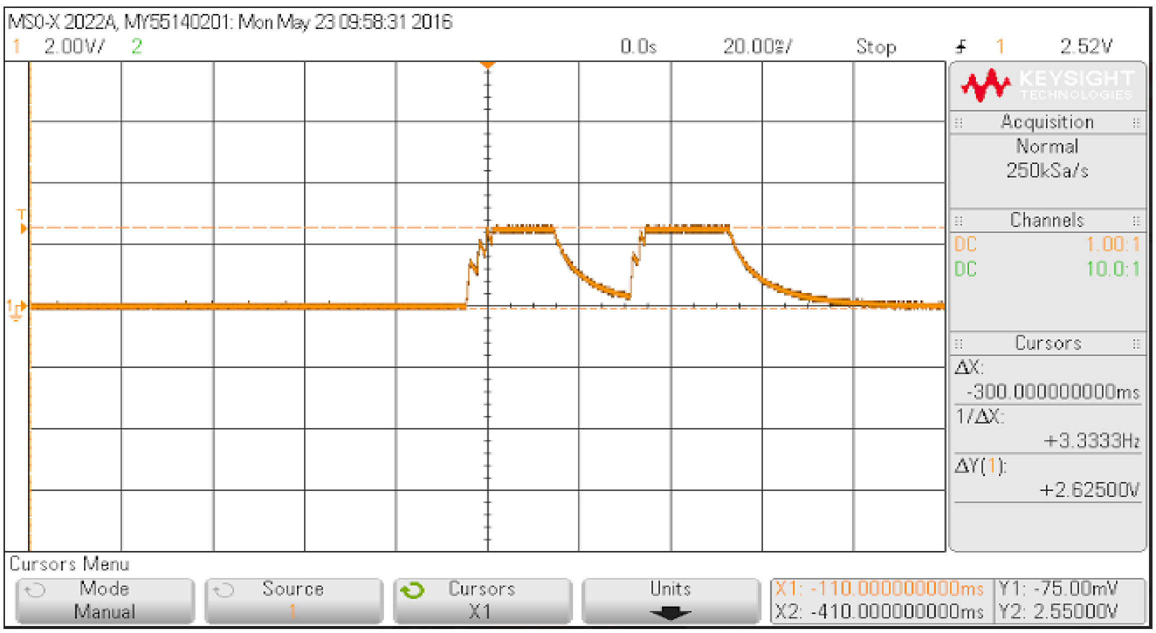

Figure 5-4: 100Ω Load Output

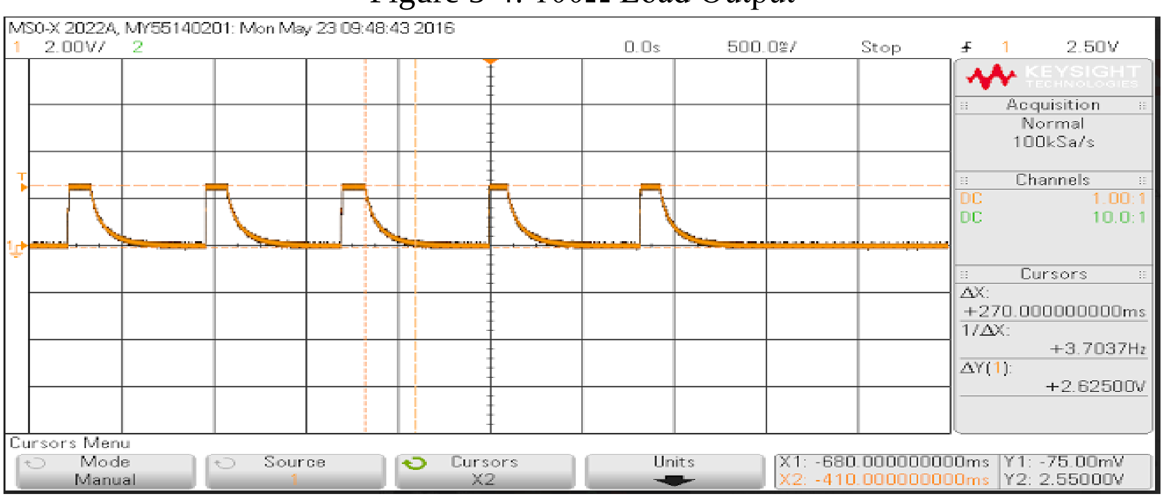

Figure 5-5: 1kΩ Load Output

The next test setup was to test the actual piezoelectric device on a rotating bike wheel to mimic real conditions. The issue that arose was the magnet as it fell through the tubing as the wheel rotated would become attracted to the metal spokes around it. The pull strength of the magnet was stronger than the force of gravity causing the magnet to not flow through the coil in turn not generating voltage. This setup can be seen in Figure 5-6 with the piezoelectric device positioned between the spokes of the rim.

Figure 5-6: Bike Wheel Test Setup

Since the bike rims' spokes are magnetized, the neodymium magnet interacted with the spokes, a different test setup needed to be designed. As shown in Figure 5-7, the output from the system was set at 2.5V. The output was connected to a resistor and LED in series. As the magnet passes through the coil of the piezoelectric device, the rectifier sets the output voltage to 2.5V. In turn, current will pass through the load causing the LED to turn as seen in Figure 5-8.

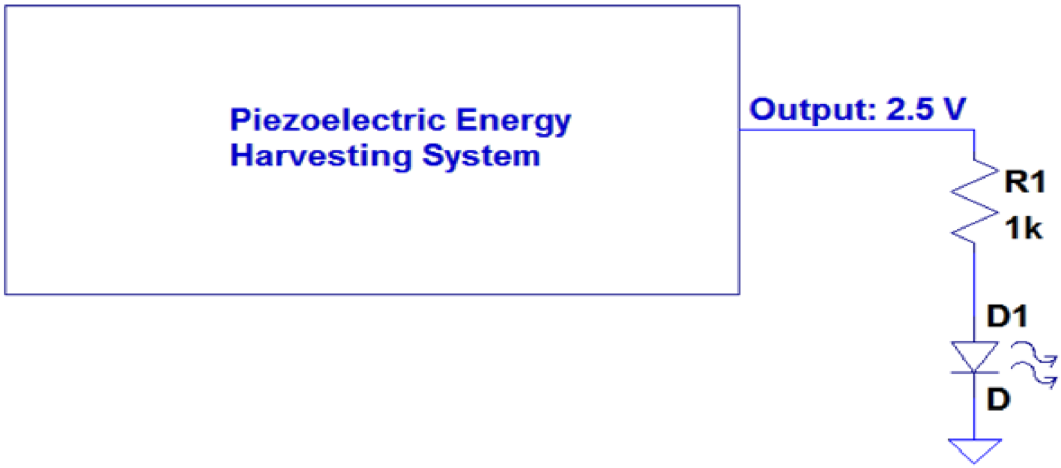

Figure 5-7: Test Schematic

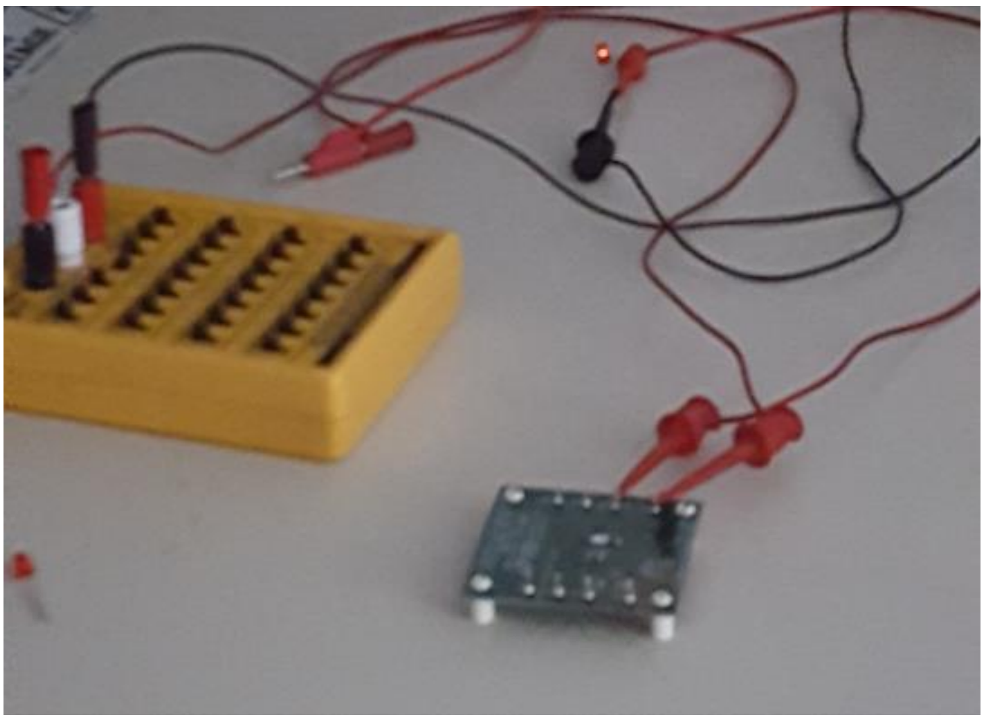

Figure 5-8: LED Load Test Setup

Table 5-1 summarizes the important parameters for both our piezoelectric device and our LTC3588-1 Demo Board. As you can see from the table our piezoelectric device outputted 18-30Vpp, a high enough voltage to be input into the next part of our system. We then verified that the next part of the system, the LTC3588-1 Demo Board, had an input range of 2.6-20V and outputted a range of 1.8-3.6V. The next step we would have taken for our original idea would have been to double that voltage to be used with a USB.

Table 5-1: Component Parameters

Piezoelectric Device			LTC3588-1 Demo Board		
Input	Output	Frequency	Input	Output	Frequency
Kinetic Energy	18-30 Vpp	1-5Hz	2.6-20V	1.8-3.6V	DC

Table 5-2 shows a comparison of our original design requirements and what our final design ended up being. Our first requirement, compact for ease of use, was achieved; however, in our original design we wanted to make a box containing all the circuitry. But as we moved through the design there was less circuitry than anticipated which allowed us to not use a box in our final design. The second requirement, able to withstand outdoor weather conditions, was no longer required due to our design not working on a bike. The third requirement, universally configurable for different bike frames, was also no longer applicable due to our system not working on a bike. The last requirement, output provides 500mA of current, was also achieved; however, we did not obtain the desired 5V output but rather our output was only 2.5V.

Table 5-2: Comparison of Original Design Requirements and Final Design

Requirement	Engineering Specifications	Final Design
Compact for ease of use	Small and portable ● Box containing circuitry (7.5 inch. tall, 3 inch. wide, 1.2 inch. deep) ● Average initial setup time should not exceed 30 minutes	Piezoelectric Device Dimensions- 7.5” Demo Board Dimensions- 2.5”x2.5”
Able to withstand outdoor weather conditions	Weatherproof casing and hermetic sealing	No longer required
Universally configurable for different bike frames	Attachment system based on either clips or magnet	Does not work on bike wheels
Output provides 500mA of current	Regulated 5V USB output and capable of charging a 3.7V Lithium Ion Battery	2.5V output, 50mA Max

Chapter 6: Conclusion

The design in the end met some of the requirements that were initially set. The major requirement that was not met was the ability to place the device on a bike wheel. The magnetic pull force of the magnet proved to be stronger than the force of gravity. This could be remedied by using a different type of tubing that insulates the magnetic field from the metal spokes of the rim. This would allow the magnet to slide back and forth as the wheel rotated. Another issue with this design was the ability to attach the entire system to the wheel. Since the wheel is constantly rotating, the entire system has to be contained on the wheel so the reference frame stays constant. As a result, the ability to charge a phone while the bike wheel turns proved to be difficult. Another complication was the coefficient of friction of the tubing. The magnet would slide slowly at times causing the voltage at the demo board to be too low to rectify properly causing the system not too work. Next, the final design could not be outputted via USB since the system currently can output a voltage of 3.6V whereas USB requires 5V to operate properly. There are two solutions to this problem. The first would be to get the LTC3588-2 which features an output range to 5V. The other possibility would be to use a DC-DC boost converter. The LTC3588-2 demo board would be the best option because it would save space on the wheel instead of having an additional integrated circuit for the boost converter. The finished design was able to drive a maximum current of 50mA and operates solely from human kinetic energy.

Appendix A

References

[1] Case Studies in System of Systems, Enterprise Systems, and Complex Systems Engineering, [Online], Available: https://books.google.com/books?isbn=1466502398
Information regarding total world energy consumption and the sources of how the energy is produced.

[2] International Energy Agency, [Online], Available: http://www.iea.org/topics/energypoverty/
Information regarding access to electricity of the global human population.

Appendix B

Senior Project Analysis

Project Title: Faraday Rechargeable Battery System

Student's Name: Alex Gasper and Bret Omsberg Student's Signature:

Advisor's Name: Taufik Advisor's Initials: Date: 6/9/16

1. **Summary of Functional Requirements**
   This project is centered around the design of a self-sustaining battery charging system that can be implemented on a wide range of bicycles. The system must be durable due to the widely-varying weather conditions that this device will be subjected to. This device must be able to provide enough current drive to power the internal circuitry of the system as well as provide current to the battery for charging purposes. In addition to providing a usable output current, the device must also be capable of charging USB powered electronics via the output USB hub located on the battery and power the lighting system on the bike.

2. **Primary Constraints**
   The primary constraint for this system is the physical size and weight. The system must be portable and light so attachment to the bike frame is simple. Since our competitor's market their small package design, our system will have to be similar in size and weight. This presents some difficulties due to the environment this product will be used. This product will be exposed to a variety of weather conditions, and will need to be weatherproof to protect the sensitive electronics inside the package. In addition to these constraints, other difficulties will come from the design process where optimization is critical. To be competitive, minimum hardware is critical to lower overall cost.

3. **Economic**
   If developed, this device can create jobs for in engineering, manufacturing, marketing, and sales. Profits will result from the development of our product and price savings will be passed to the consumer via their energy bill. Our product uses silicon, plastic, a magnet, and a battery. A large portion of the cost will come from the individual component prices. The projected payback will be seen by the consumer in the form of lower energy bills.

Table B-1: Estimated Costs

Item	Quantity	Company	Cost
Neodymium Magnet	1	K&J Magnetics	$11
Magnet Wire	1	Digikey	$18
LTC3588-1 Demo Board	1	Linear Technology	$200 (donated)
Lithium Ion Battery	1	Alibaba	$4
USB Connector	1	Digikey	$0.50

As you can see from Table 9 above the total estimated costs for our product will be around $33.50 with a retail price between $30-$50.

4. **If Manufactured on a Commercial Basis**

If this system was to be manufactured at a high volume, the cost per component would be less due to pricing from manufacturers generally decreases with the number of products ordered. The approximated cost of production can be seen in Table 10 below.

Table B-2: Long Term Cost Analysis

Manufacturing Estimation	**Estimated Cost**
Estimated Purchase price for each device	$30
Estimated number of devices sold per year	1,000
Estimated Manufacturing cost for each device	$12
Estimated Profit per year	$18,000

5. **Environmental**

The environmental impacts are mostly beneficial. This device uses “free energy” that normally would be lost and converts it into usable electricity. The electricity that is generated is clean and renewable. The electricity that is used from this system to charge devices such as cell phones will decrease the demand for electricity supplied from the power grid, and in turn reduce carbon emissions from power plants that normally would have to supply this electricity and transmit it across many miles of power lines just to reach the end user. With any manufacturing process, there are certain materials that are necessary for production. In this process, the manufacturing of the printed circuit boards will utilize energy as well as silicon and other materials.

6. **Manufacturability**

This design utilizes some pre-built components including integrated circuits. The cost and manufacturability of these components will have a direct effect on the end product. The availability of these products will partially determine the rate and lifespan of the manufactured product. The manufacturability also relates to the optimization of the design. If the design is not optimized, the product will require more components which will cause the manufacturing process to be more expensive and more difficult.

7. **Sustainability**

Our system is targeted at environmentally conscious people which means the system must be durable and have a long product lifespan. Since manufacturing is an energy intensive process, we want our product to have a long lifespan to reduce the environmental impacts of manufacturing. A major hinderance of increasing the lifespan of our product is due to weather conditions that this device will be subjected to.

8. **Ethical**

The major ethical issues for this product come from the sustainability of the product itself. Some companies design their products to have a limited lifespan to increase the sales of the product, but our product will be designed to last. One design consideration we took to improve the longevity of the product is using the hermetic seal to prevent moisture from entering the device.

9. **Health and Safety**

The rechargeable system has very little health concerns associated with it. The electricity that is generated is low voltage and low power. The major safety issue associated with this device is the danger that comes with riding a bicycle, and not the device itself. On the contrary, this device produces clean, sustainable energy instead of having electricity generated from a coal plant that pollutes the atmosphere and is known to cause asthma attacks, heart attacks and even premature death.

10. **Social and Political**

The change to renewable energies around the world has been prevalent over the last decade. This technology is just a continuation of this trend. The clean electricity that is generated from our product may prevent pollution coming from coal power plants to enter the atmosphere because the electricity no longer needs to be produced for that device. It may seem insignificant, but if thousands of these devices were implemented, the power grid would have to produce a lot less power reducing the overall carbon emissions emitted from these plants.

11. Development

From the development of our rechargeable battery system we were able to learn a few new techniques pertaining to power electronics. Because our input to the system relies on a wheel rotating the input will be an AC wave, we were forced to develop a rectifier into our system. In power electronics rectifiers are used to convert alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The other power electronics technique we used in our system was a DC-DC converter. We needed the DC-DC converter to boost the output of our rectifier to allow for storage in a batter for future use via USB connection.